TECHNICAL RESEARCH REPORT

The Hybrid Motor Prototype: Design Details and Demonstration Results

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The Hybrid Motor Prototype: Design Details and Demonstration Results

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ABSTRACT

A novel hybrid rotary motor incorporating piezoelectric and magnetostrictive actuators[1] has been designed and demonstrated. The novelty of this motor was the creation of an electrical resonant circuit, whereby reactive power requirement on the power source is reduced. It was envisaged that the motor would be suitable for low output speed, high torque applications because of its design. This report presents the constructional details of this motor and the results of the demonstration.

1 Introduction

The motivation behind the development of a novel hybrid rotary motor was described in an earlier report.[1] It was shown that electrically, the piezoelectric and magnetostrictive actuators behave like a capacitor and an inductor respectively. Thus by creating an electrical resonant circuit, the reactive power requirement on the power source is reduced. The report contained theoretical modeling of the hybrid motor taking into account impact effects, stiffness properties of the materials used, eddy current effects in the magnetostrictive material etc. Computer simulations were carried out to show the feasibility of the concept. Because of the extremely small displacements involved (of the order of microns), building a prototype motor was an exciting engineering challenge. The design and construction was carried out at the Physics Shop at the University of Maryland at College Park (UMCP), while the testing and demonstration was done at the Intelligent Servosystems Laboratory at UMCP. This report details the design features of a prototype hybrid motor (Figure 1) and the results of its successful demonstration.

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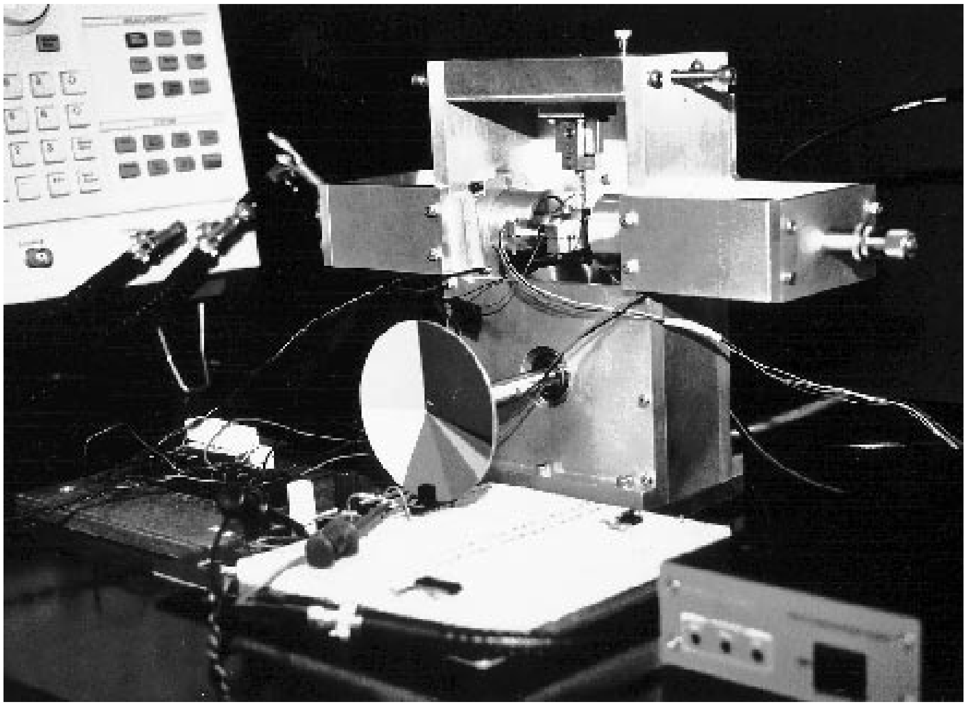

Figure 1: The prototype hybrid motor.

2 Basic Principle of Operation

Before we discuss to the technical details of the prototype hybrid motor, we first look at its principle of operation. The basic scheme of the proposed actuator is shown in figure 2. The piezoelectric stack clamps the mass m to the disc while the magnetostrictive rod pushes the mass tangential to the disc. As the angular displacement of a disc of radius 5 cm in one such push is of the order of 10^{-4} radians, we can achieve an appreciable displacement per second by operating at sufficiently high frequency. We can use another magnetostrictive rod as shown in figure 3 to achieve bi-directional motion. In figure 3, rod 2 contracts in length when rod 1 expands and vice versa.

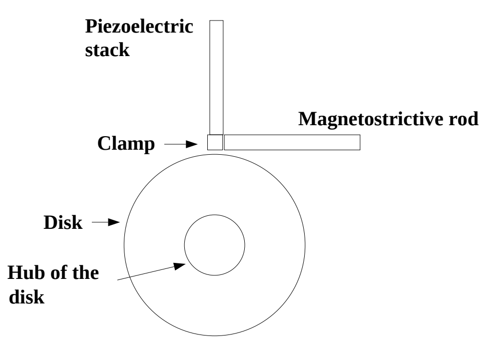

Figure 2: Basic scheme for an unidirectional hybrid motor.

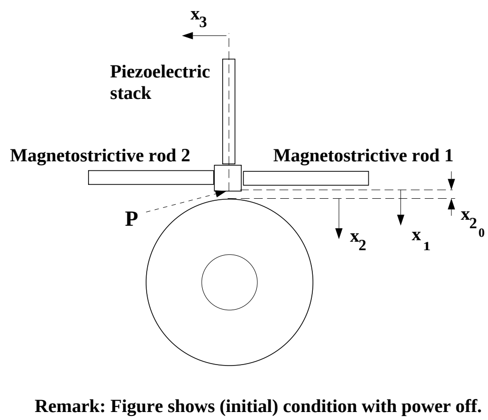

Figure 3: Schematic diagram of the actuator.

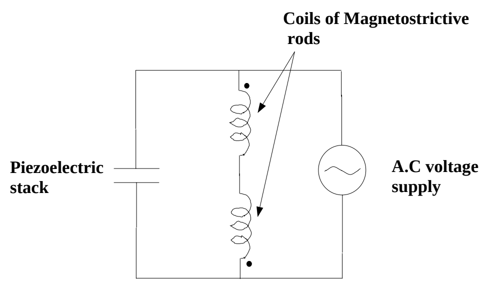

Figure 4: Electrical connection.

The electrical connection of the actuator elements is shown in figure 4. Both the magnetostrictive rods have an identical permanent magnet bias. But their coils are connected such that the current adds to the flux for one rod(which elongates), while it subtracts for the other (which contracts). This achieves motion of the disc in one direction. If the coil connections are reversed then we can achieve motion in the opposite direction.

During one cycle of the applied voltage, the actuator has two distinct phases of operation.

1. The piezoelectric stack and the clamp unit are in 'good contact' (i.e clamped) with the disc.
2. The piezoelectric stack and the clamp unit are not in 'good contact' with (i.e separate from) the disc.

Besides, impacts take place when the piezoelectric stack and the clamp unit come into contact with the disc after separation. The disc, the clamp and the piezoelectric stack are elastic and hence can undergo deformation. The magnetostrictive material has finite resistivity and hence eddy currents can circulate within the material if the frequency of operation is sufficiently high. These effects were taken into account while building a simulation model of the system.[1]

3 Mechanical Design and Assembly

The aim of the prototype was to show proof of concept. Hence, reducing the size of the actuator was not considered a priority and commercially available components were used as much as possible to keep the cost low.

Though the basic scheme of the hybrid motor is simple, the constructional details of the prototype are quite complex.[1] Since the elongation of the piezoelectric stack and the magnetostrictive actuator is in the order of microns, initial adjustments are crucial to the motor's performance. To be able to make the required adjustments and keep the cost of the prototype motor low, compromises had to be made leading to simplicity of design.

The motor itself can be thought of being comprised of two halves—a top half and a bottom half (Figures 5 and 6). The top half consists of the piezoelectric stack, the two magnetostrictive actuators, the clamping piece, and the top slide for aligning the axis of the piezoelectric stack with the center-line of the disc. The bottom half consists of the disc. The two halfs are joined by a vertical slide which is used to position the clamp against the disc. The positioning device in both the slides is a differential screw which has a resolution of 1 micron. This makes accurate positioning possible.

The two halves of the hybrid motor are first assembled separately and can be tested before being put together. The assembly of each of the halves is straightforward. For successful operation it is necessary that the two magnetostrictive actuators and the clamp are snugly assembled. While doing this assembly for the prototype demonstration, it was observed that the steel balls between the clamp and the magnetostrictive actuators would get wedged improperly, so that there is some room for the actuators to expand without resistance. This was a major cause of poor actuation during early tests of the hybrid motor. It was found that adjusting the differential screws on the side (Figure 5) was not enough to make the steel balls fall back into the cavities designed for them. Another important adjustment is that of the height of the clamp above the disk. First the clamp is adjusted so that there is no motion of the disk. Then the clamp is raised with the help of the micrometer attached to vertical slide so that the disk is able to rotate with some resistance to its motion. Then the sinusoidal power supply is turned on with the voltage amplitude between 30 and 40 volts and the frequency between 650 and 750 Hz. Experiments showed us that the hybrid motor shows good motion in this frequency range (Figure 12). Then the differential screw is adjusted finally to obtain best motion. It is possible that the motion is still not in the range of 3 - 3.5 RPM as obtained in the demonstration (Figure 12). Then it is important to make sure that the clamp and the piezoelectric stack assembly is "centered" so that they are in line with the center line of the steel disc (Figure 5). This is done with the help of the differential screw attached to the top slide.

4 Demonstration Results

Before proceeding to test the entire hybrid motor system, a test of the individual actuators was done. As explained later, the piezoelectric stack was only tested to make sure that it clamped onto the disc for some D.C voltage while being separated for zero voltage. An LVDT transducer system[2] was used to measure the displacements of the Terfenol-D actuators. The LVDT Sensor was mounted on the hybrid motor as shown in Figure 7. This scheme was chosen because one could then easily measure the relative displacements of the two actuators, and if one of them was not supplied any power then one could measure the total displacement of the other actuator. Figure 8 shows the displacements obtained from the two magnetostrictive actuators.

Figure 8(a) compares the displacements for a maximum input current of 0.19 Amperes and an input frequency of 1 KHz. The comparison should be done only in terms of maximum amplitude and not in terms of phase because when one of them was on, the other was off. Similarly Figure 8(b) compares the displacements for a maximum input current of 0.45 Amps and an input frequency of 1 KHz. It can be seen that the left actuator gives larger displacements for comparable input current values. Though some disparity was expected because their individual factory-measured characteristics were as given in Figures 9(a) and 9(b), what was actually obtained was much more. In fact a complete characterization of the behaviour of the magnetostrictive actuators was carried out[2] and the results are as shown in Figure 10.

Figure 10 only shows the difference in the characteristics at an input frequency of 0.5 Hz, but one can expect

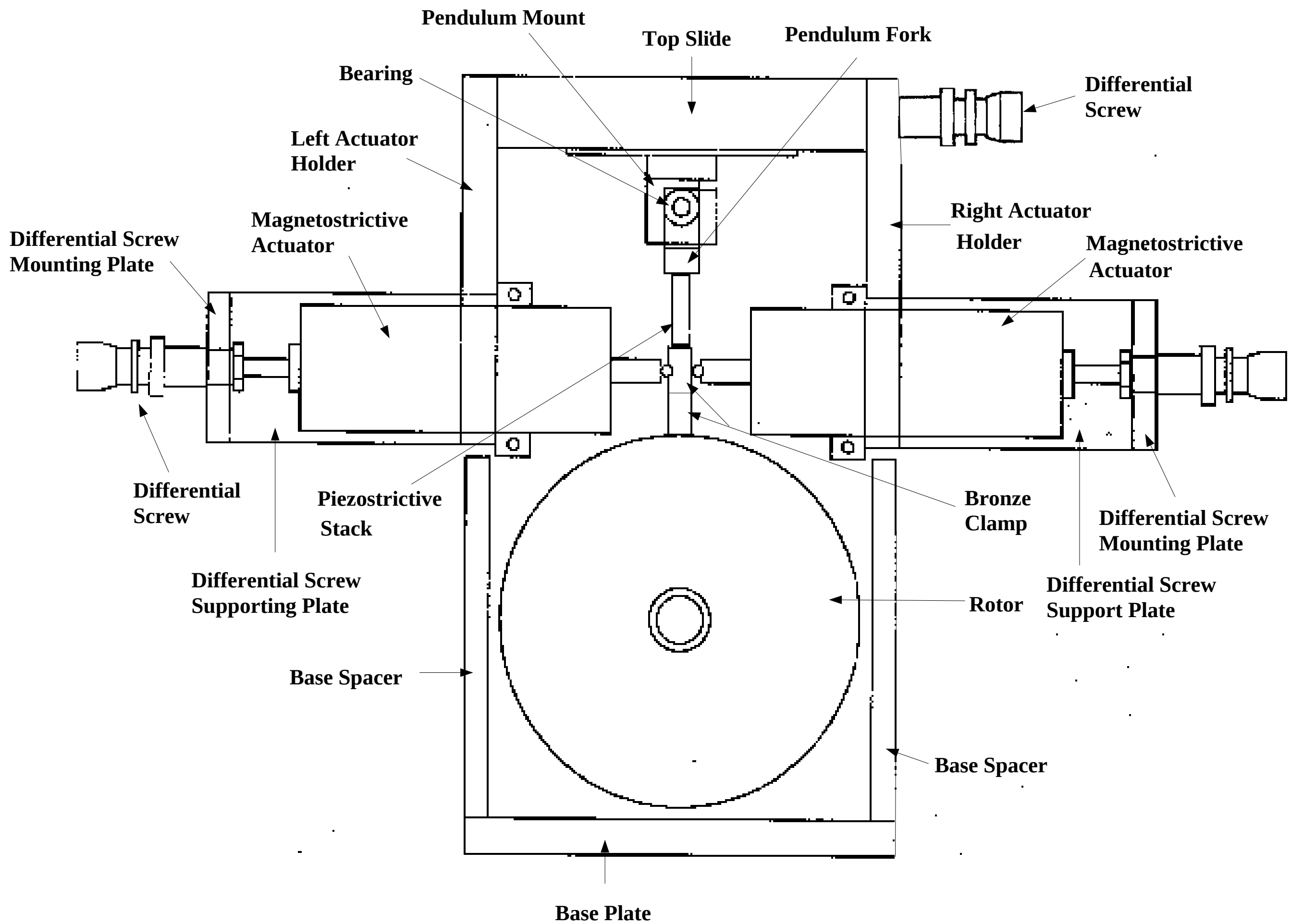

Figure 5: The front view of the hybrid motor.

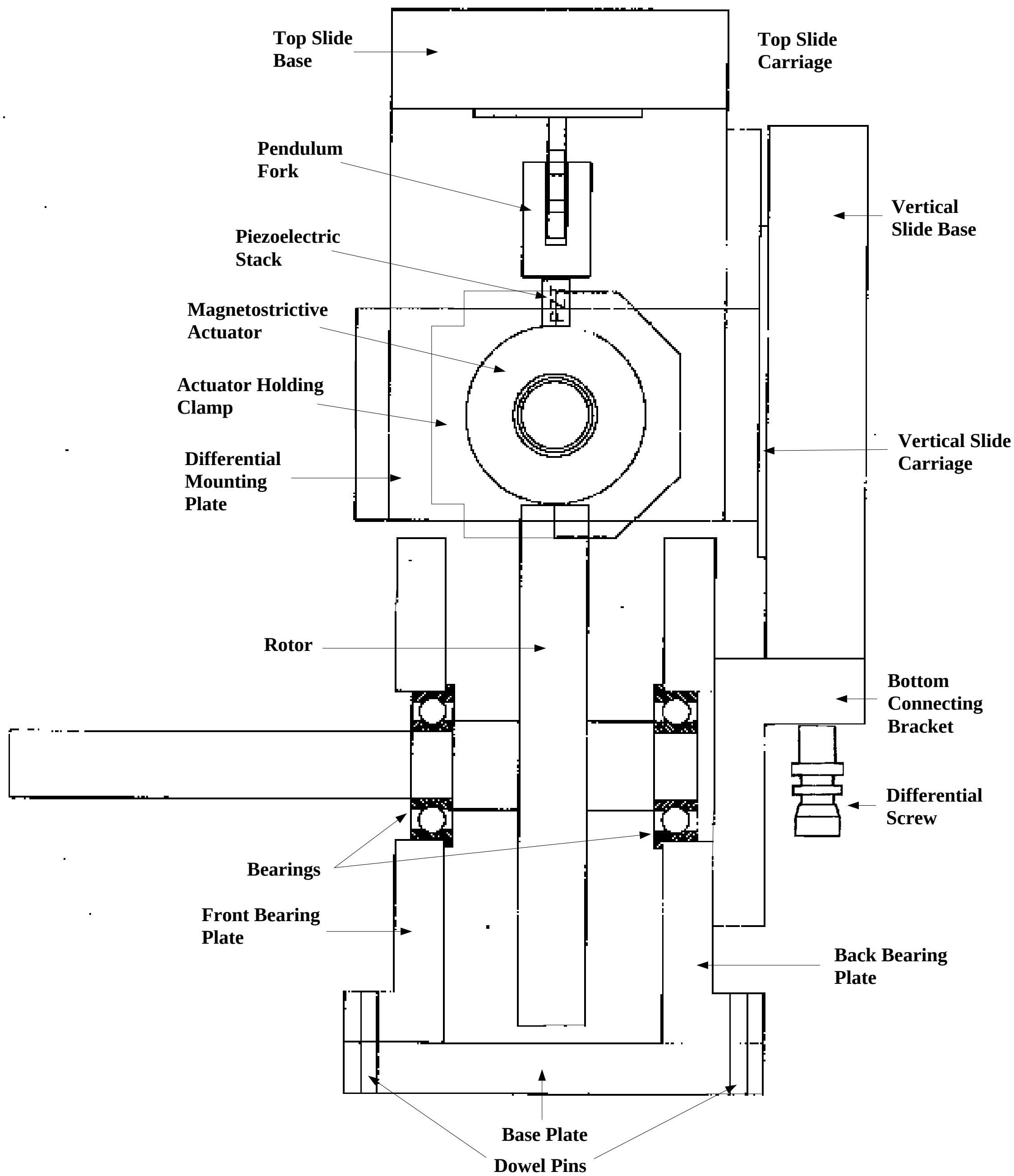

Figure 6: The side view of the hybrid motor.

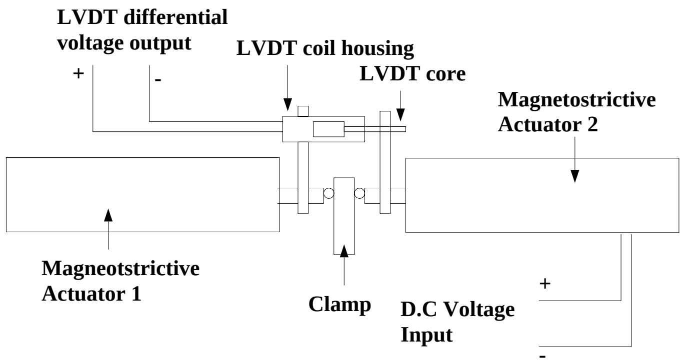

Figure 7: Schematic of the displacement sensing by the LVDT sensor.

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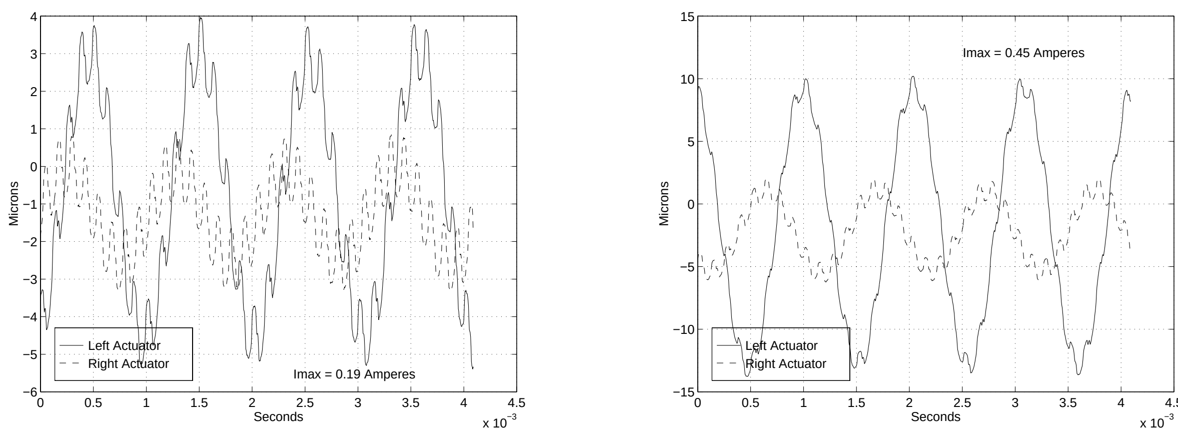

(a) The displacements for Imax = 0.19 Amps.

(b) The displacements for Imax = 0.45 Amps.

Figure 8: Comparison of the maximum displacements of the two Terfenol-D actuators.

a similar disparity at high frequencies also (Figure 8). (By left actuator we mean the actuator that is to our left as we view the hybrid motor from the front.) So we can conclude that the left actuator is working as expected while the right actuator is not. The testing of the hybrid motor was done in spite of this deficiency.

As was mentioned before in the section on basic principle of operation (Figure 4), it is necessary that the two magnetostrictive actuators be connected electrically, so that the flux adds to the permanent magnet bias for one of them and subtracts for the other. Figure 11 shows the net displacements obtained for two different connections of the actuators. Ideally, we would like one of them to be zero, but in our case, we have to choose the connection with the lower relative displacement, and consistently use this for all the later experiments.

For successful operation of the motor, it is enough that the piezoelectric stack extend sufficiently to clamp the disc, while separating from it during the other half cycle. By the design, one can see that the placement of the top half with respect to the bottom half is critical in making sure that both clamping and separation occur. Hence in the actual demonstration, the placement of the top half was carried out with power being supplied to the device, the criterion being most rotary motion at some frequency of operation. Figure 12 shows the variation of no-load speed of the hybrid motor with frequency, with the input voltage being a sinusoid with a peak of 40 Volts. The two curves correspond to the experiments performed on 8/22/95 and 5/1/96 respectively, as explained by the legend. As can be seen, there is a band of frequencies approximately 650 - 750 Hz, where the no-load speed is consistent, while there is a noticeable difference in the band for positive motion. This can be easily explained by the critical dependence of the motion obtained on the position of the clamp vis-a-vis the disc. Any change in the position would give rise to a different characteristic. At higher frequencies the impedance presented by the magnetostrictive actuators is higher and as a result the current through them is smaller. This results in a smaller magnetostrictive actuation and lesser no-load speed for the hybrid motor. On the later date (5/1/96) both the clamp and the disc had undergone some wear and tear, and so the situation is not exactly identical. However, in the most important band for 'good' motion, the wear and tear is not so consequential. This brings us to the important question of choice of frictional materials and there is much study to be done in this area. In their book, S.Ueha and Y.Tomikawa[3] have published some interesting details of the performance and life of ultrasonic motors with different frictional materials. As explained before, the goal of the prototype was only to show proof of concept, and the question of the best frictional materials was not pursued any further.

Finally, in an attempt to improve the performance of the motor, the prestress of the defective right Terfenol-D actuator was changed, and the result is shown in Figure 13. As can be seen the maximum frequency has increased a bit, but the band for good motion has reduced. Another fact that must be mentioned is that it was observed that even for good motion the clamp did not make very good contact with the disc, with contact area being less than 10% of the area of the clamp. The contact area was perhaps insufficient due to some misalignment. It can naturally be expected that with better contact, the performance of the motor would also be much better.

5 Conclusion

This report shows proof-of-concept for a novel hybrid rotary motor built with piezoelectric and magnetostrictive materials. Though the principle of operation is simple, the construction of a working prototype of low cost is a very interesting design challenge. This challenge was successfully met even though some new difficulties cropped up after the design stage. The prototype hybrid motor that was demonstrated at the Intelligent Servosystems Laboratory at the University of Maryland is by no means an optimal design, and this study suggests possible means to improve its performance.

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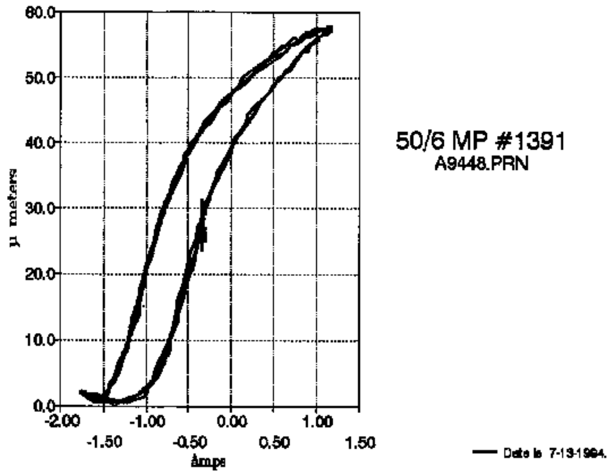
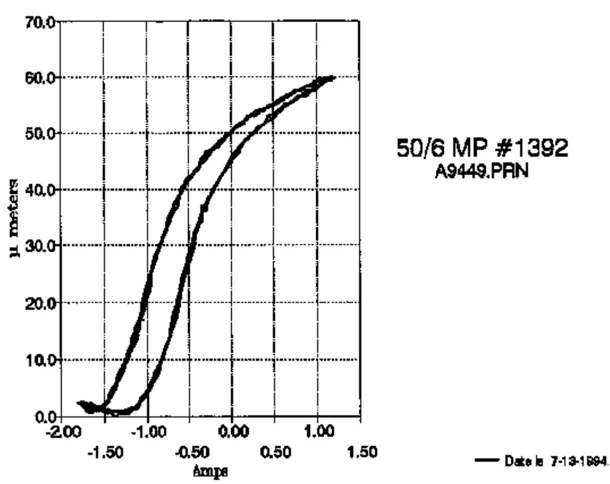


(a) The displacement vs input current curve for actuator 1.



(b) The displacement vs input current curve for actuator 2.

Figure 9: Characteristics of the magnetostrictive actuators.

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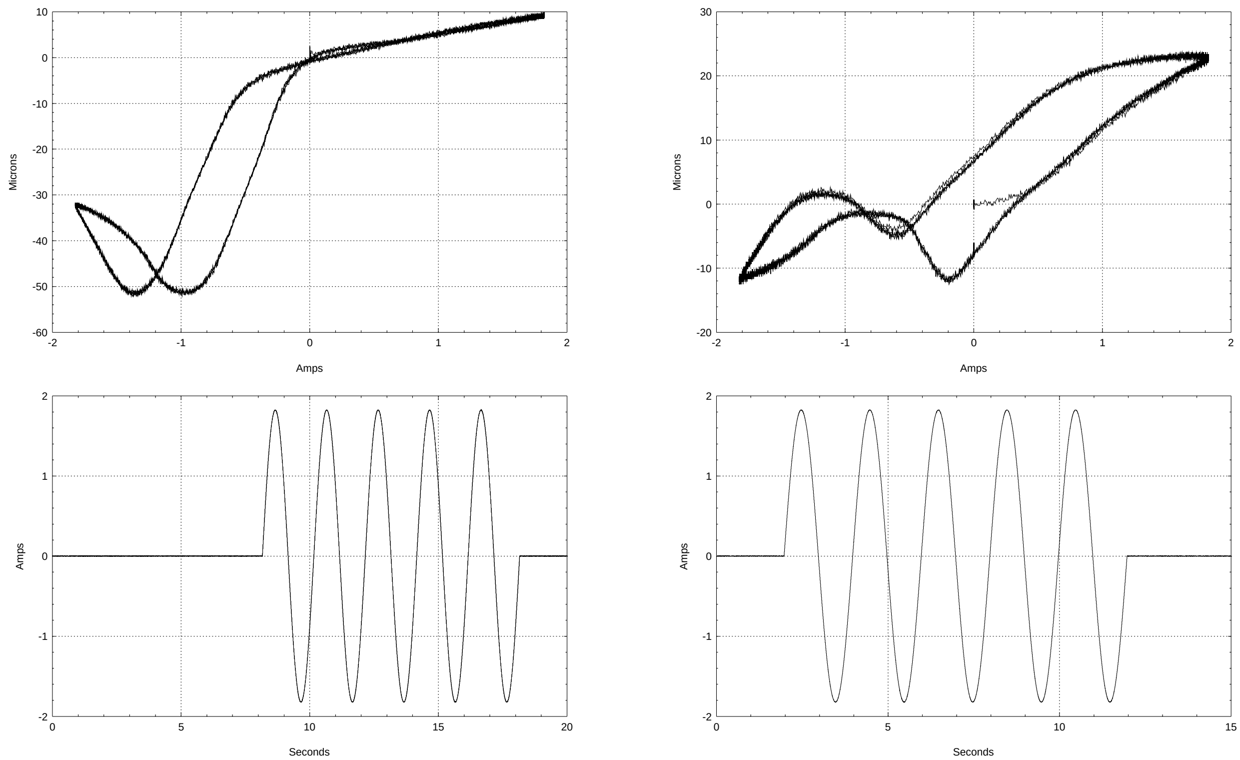

(a) Left Actuator Characteristic.

(b) Right Actuator Characteristic.

Figure 10: Comparison of the characteristics of the two Terfenol-D actuators.

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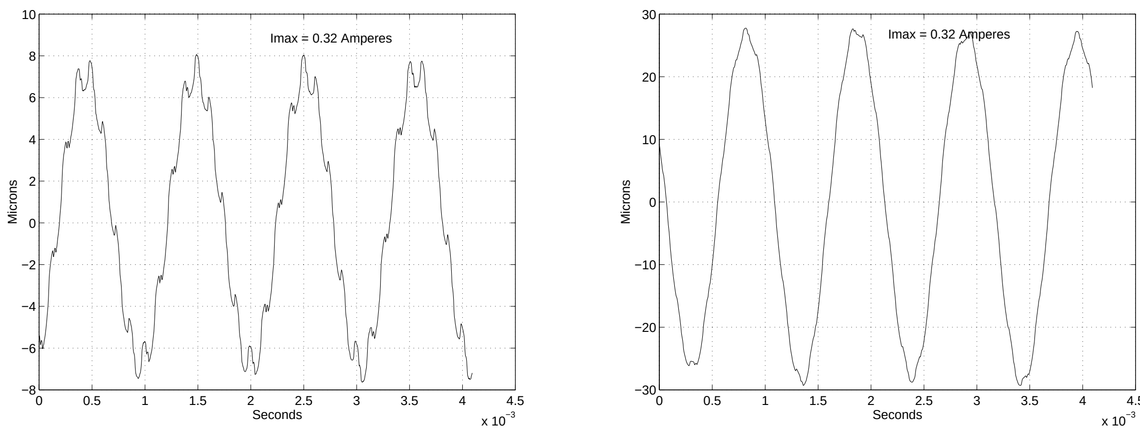

(a) The displacements for the black wires tied together.

(b) The displacements for one black and other red wire tied together.

Figure 11: Net displacements obtained with two different connections of the Terfenol-D actuators.

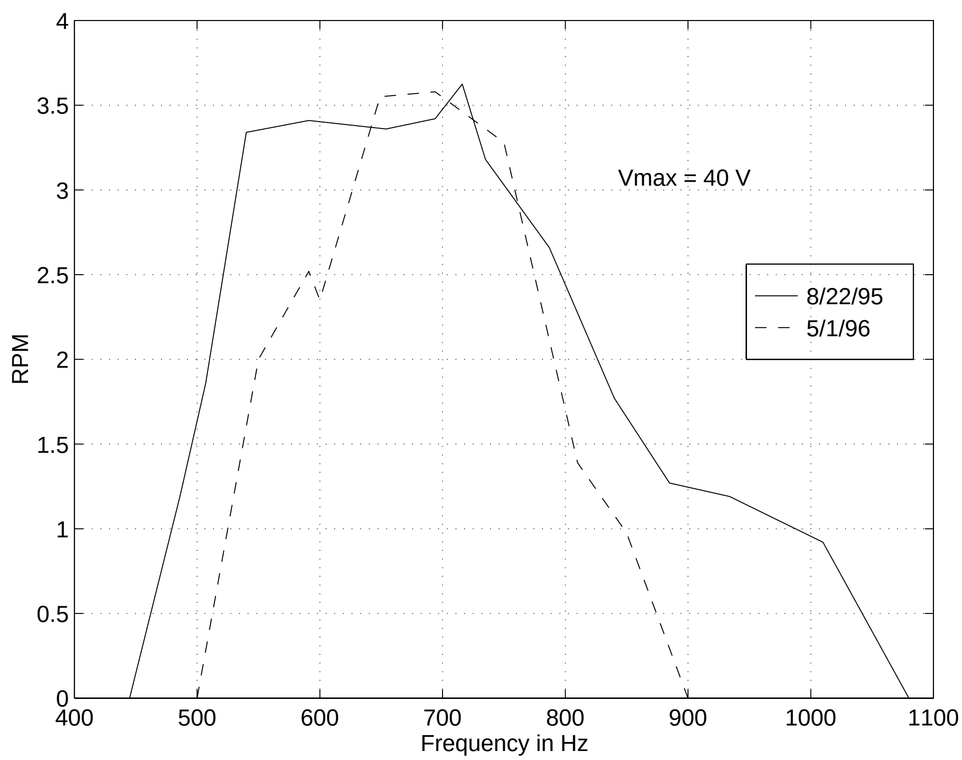

Figure 12: Variation of No-load speed with driving frequency.

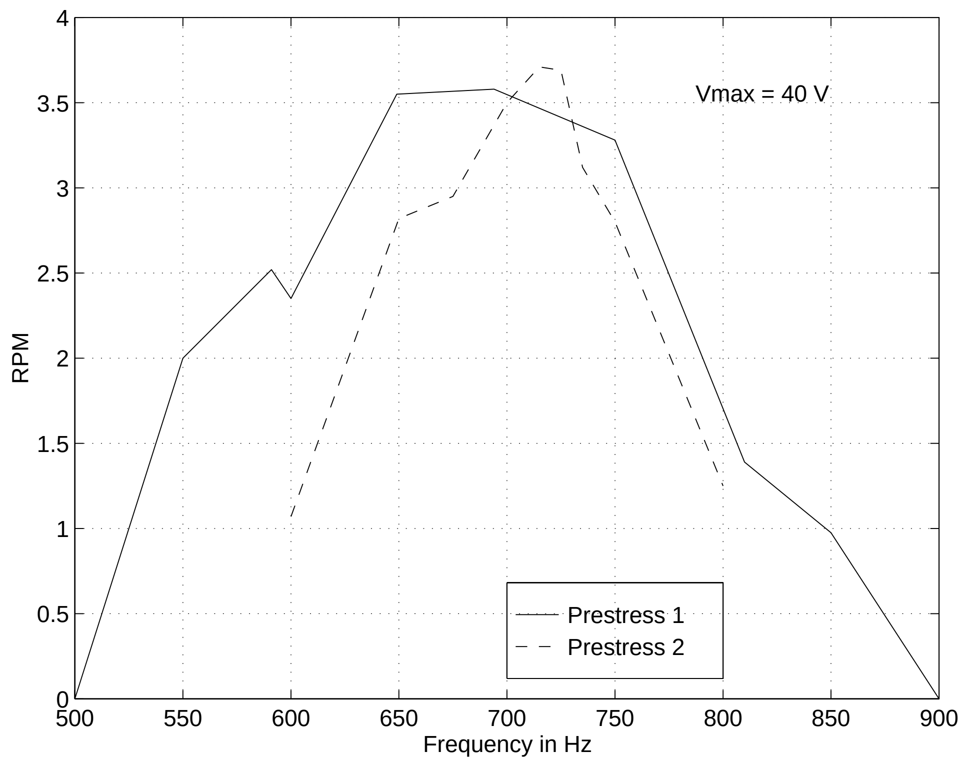

Figure 13: No load speed versus frequency for 2 different prestresses on the Right Actuator.

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[3] S. Ueha and Y. Tomikawa, *Ultrasonic Motors: Theory and Applications.* Clarendon Press, Oxford, 1993.